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No. 1143

FUNDAMENTALS OF THE CONTROL OF GAS-TURBINE
POWER PLANTS FOR AIRCRAFT

PART II

PRINCIPLES OF CONTROL COMMON TO JET, TURBINE-PROPELLER
JET, AND DUCTED-FAN JET POWER PLANTS

By H. Kühl

Translation

"Grundlagen der Regelung von Gasturbinentriebwerken für Flugzeuge.
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ZTL-Triebwerken." Deutsche Luftfahrtforschung, Forschungsbericht
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FUNDAMENTALS OF THE CONTROL OF GAS-TURBINE

POWER PLANTS FOR AIRCRAFT*

PART II

Principles of Control Common to Jet

Turbine-Propeller Jet, and Ducted-Fan Jet[1]

By H. Kühl

SUMMARY

After defining the aims and requirements to be set for a control system of gas-turbine power plants for aircraft, the report will deal with devices that prevent the quantity of fuel supplied per unit of time from exceeding the value permissible at a given moment. The general principles of the actuation of the adjustable parts of the power plant are also discussed.

INTRODUCTION

In part I of the report (reference 1) of these investigations, a course of reasoning was pursued and conclusions were drawn, which make possible a simplified representation of the behavior of gas-turbine power plants for aircraft under various operating conditions. In the present paper those principles of control that are common to TL, PTL, and ZTL[1] power plants will be set forth. The control of jet engines will be treated in detail in the concluding third part of the report. Subsequent reports will deal with investigations on the control of turbine-propeller jet and ducted-fan jet power plants.

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*"Grundlagen der Regelung von Gasturbinentriebwerken für Flugzeuge. Teil II - Gemeinsame Prinzipien der Regelung bei TL-, PTL- und ZTL-Triebwerken." Deutsche Luftfahrtforschung, Forschungsbericht Nr. 1796/2. Deutsche Versuchsanstalt f. Luftfahrt E. V., Inst. f. motorische Arbeitsverfahren und Thermodynamik, Berlin-Adlershof, ZWB, July 9, 1943.

[1][NACA comment: jet, TL; turbine-propeller jet, PTL; ducted-fan jet, ZTL.]

I. TASKS OF CONTROL SYSTEM.

A system for control of the power output of gas-turbine power plants for aircraft under various operating conditions has substantially the following tasks:

1. In order to avoid any possibility of injury to the engine, it is necessary to prevent the overstepping either of the permissible gas temperature ahead of the turbine or of the permissible speed and to prevent the operation of the compressor in the unstable portion of its range. Because operation of the compressor in the unstable region always causes a decrease in the power-plant output and an increase in the specific fuel consumption, such operation is to be avoided as far as possible even when the question of direct damage to the engine is not involved.

2. The adjustable parts[2] of the engine, those parts of the component units with the exception of the devices for fuel supply, the setting of which may be altered during operation, (for example, jet nozzle, adjustable pitch propeller), are to be so actuated that, as far as this is possible without endangering the engine, when the pilot's manual control lever is set at "full power" the highest possible output is actually attained at all possible operating conditions (flight speed, atmospheric pressure, and temperature); and when set at part load as advantageous a fuel consumption as possible will be secured, at least under the more frequently occurring operating conditions.

Some of the requirements mentioned in 1 can generally be realized in the actuation of the adjustable parts. Insofar as this is not the case, the basic means of fulfilling the requirements mentioned in 1 is the limitation of the quantity of fuel supplied.

The arrangements for a direct limitation of the fuel quantity are the same in principle for jet, turbine-propeller jet, and ducted-fan jet power plants and therefore all three will be treated together. However, under certain circumstances, the possibility exists, for instance with the jet engine, of simplifying the control system by means of indirect limitation of the quantity of fuel.

For the second task, only certain general principles can be set forth; the means of carrying out these principles in detail will

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[2]Designated "adjustable regulating devices" in part I.

differ in the case of each type engine. In this connection, specific investigations must be made to determine which parts it is necessary or desirable to make adjustable.

There are a number of possible variations of the manner in which the control devices may be set in motion in accord with a movement of the manual control lever by the pilot. For example, the pilot may select the quantity of fuel supplied to the engine by movement of the power lever; in this case, the devices for limiting the quantity of fuel, as well as the adjustable parts, are to be actuated by the automatic control system. The adjustment may also be such that each setting of the power lever corresponds to a certain speed to which the lever brings the motor by altering the amount of fuel supplied. In accordance with the type regulation selected, the control devices may take various forms; nevertheless, in many cases a part of the control devices can remain unchanged at least in principle.

All power plants to be discussed here have these features: an impact scoop, a compressor, a combustion chamber, a turbine that drives the compressor, and a jet nozzle behind the turbine. Figure 1 shows a diagram of a jet power plant.

The following symbols will be used throughout this report:

w_0 flight speed, (m/sec)

$Ma_0 = w_0/\sqrt{g\kappa_L R_L T_0}$ Mach number of flight speed

n engine speed, (U/min)

p_0, T_0 pressure and temperature of atmosphere, (atm absolute, $^\circ K$)

p_1, T_1 pressure and temperature ahead of compressor, (atm absolute, $^\circ K$)

p_2, T_2 pressure and temperature behind compressor, (atm absolute, $^\circ K$)

p_3, T_3 pressure and temperature ahead of turbine, (atm absolute, $^\circ K$)

Based on gas at rest at stagnation point and given moment

p_4, T_4	pressure and temperature behind turbine, (atm absolute, $^\circ K$)
T_5	temperature behind jet nozzle, ($^\circ K$)
V_1	volume of air entering compressor per unit time based on gas at rest at stagnation point, (m^3/sec)
G_L	weight of air per unit time, (kg/sec or kg/hr)
[3]B	weight of fuel per unit time, (kg/sec or kg/hr)
$m = \dfrac{B}{G_L}$	fuel-air mixture ratio
S	thrust, (kg)
[4]$b_S = \dfrac{B}{S}$	specific fuel consumption, (g/kg sec or kg/kg hr)
F_t	flow area of turbine nozzle at narrowest point, (m^2)
F_d	flow area of jet nozzle, (m^2)
$\sigma = \dfrac{S}{F_t\, p_o}$	thrust coefficient, that is, jet thrust produced per unit of turbine nozzle flow area when $p_o = 1$
g	acceleration due to gravity, (m/sec^2)

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[3]Changed from the G_K used in part I in the interest of standardization.

[4]Changed from part I with a view to standardization (b_s is lubricating oil consumption).

R_L, R_G gas constants for air and
                             combustion gases, respec-
                             tively, (m/degree)

κ_L, κ_G exponents of adiabatic curve
                             for air and combustion
                             gases, respectively

For certain investigations, a characteristics diagram for the compressor is necessary. As such a characteristics diagram was unavailable, a diagram was computed on the basis of measurements made by the AVA at Göttingen[5] on single stages with the use of simplifying assumptions. Figure 2 shows this characteristics diagram, which was constructed on the basis of the principles of similarity, (references 1 and 2) in a form valid for various intake temperatures T_1. In the diagram, lines of constant value of T_3/T_1 are plotted, which, as previously shown, are very well approximated by straight lines through the zero point, if the flow area of the turbine nozzle is constant and the gas attains critical velocity.

II. CONTROL DEVICES FOR DIRECT LIMITATION

OF QUANTITY OF FUEL SUPPLIED

1. Determination of Quantity of Fuel Supplied

The desire for simplicity has led to the general use in gas-turbine power plants of fuel pumps, which without means of direct measurement of fuel quantity (for example, geared pumps and centrifugal pumps) supply a greater quantity of fuel than is needed; the excess fuel flows off through an overflow valve. In contrast to the Otto engine in which the regulator controls the quantity of fuel per working cycle, here the regulator controls the quantity of fuel per unit time.

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[5]The results were very kindly placed at my disposal by Diplom-Ingenieur Encke, for which the most cordial thanks are herewith expressed. The blade form used as the basis of the calculations was chosen because of the flatness of the corresponding characteristic curves. Other forms would have yielded greater pressure heads. As a margin of safety in practical designing, the efficiency coefficients were chosen somewhat smaller than the measured values.

The alteration of the quantity of fuel injected into the combustion chamber is most simply accomplished by altering the injection pressure, that is, the pressure difference at the injection nozzles. Only if the atomization became too poor when small fuel quantities were being used, would it be necessary to use regulation by means of alteration of the nozzle flow area (alteration of the area of each nozzle or cutting in and out of one or more nozzles) with or without simultaneous alteration of the injection pressure. As long as regulation is not required to accomplish an exact and direct determination of the quantity of fuel per unit time, it will suffice, if at the appropriate times, the setting of the overflow valve or of the injection-nozzle flow area is altered in the required direction. However, an exact determination of the quantity of fuel per unit time is a prerequisite of some of the arrangements to be subsequently described and therefore the possible means of accomplishing this determination will be investigated first.

The quantity of fuel per unit time is fundamentally determined by the pressure difference at the injection nozzles and the nozzle flow area. However, it is not immediately certain that control by means of these factors is sufficiently exact or reliable in view of the danger of the malfunction of an individual nozzle, for example, by clogging. More favorable conditions for control will be obtained if the pressure drop at some constriction in the fuel line is used for the evaluation of the quantity of fuel being supplied, as shown in figure 3.

In this fuel line, between the pump a and the injection nozzles b a constriction c is inserted, the flow area of which may be varied by axial movement of the throttle unit d. By means of a diaphragm e or similar device upon which the pressure difference at the constriction operates, an overflow valve f ahead of the constriction is so adjusted (either directly or with the aid of a servomotor) that the pressure difference at the constriction c remains constant.[6] At the constant pressure drop in the constriction, each value of the flow area at the point of constriction then corresponds to a particular quantity of fuel flowing through per unit

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[6]Instead of altering the flow area of the constriction, the value of the pressure difference to be maintained at the constriction may be altered, the constriction area remaining the same. However, very small pressure differences would then be obtained at low fuel consumptions so it would become difficult to keep within the permissible limits of error. The same statement applies to the utilization of the pressure drop at the injection nozzles to accomplish regulation.

time.[7] In the model design shown, the pressure difference at the
injection nozzles is indirectly varied by the regulator. If it is
desired to regulate the injection-nozzle flow area at the same time,
this regulation may also be controlled by the diaphragm e.

An exact determination of the quantity of fuel supplied per
unit time is necessary primarily when a limit must be set by the
regulating arrangements, described subsequently, to the variation
of the quantity of fuel. In the rest of the range, an exact
measurement of the quantity of fuel supplied is often not required;
the quantity of fuel in that case may be set by means of a simple
overflow valve g between the pump and the constriction c. The
regulator h will then set the flow area of the constriction c at
the value corresponding from moment to moment to the maximum permis-
sible fuel quantity and the overflow valve f will open only when
this maximum permissible fuel flow is reached.

If an exact control of the quantity of fuel per unit time is
required throughout the entire range, this control must be effected
by movement of the throttle unit d. Fuel limitation by the regu-
lator may occur through a system of levers in a manner similar to
the limitation of the throttle valve opening by the pressure regulator
in the Otto engine; the regulator may change the position of a stop
that would directly limit the variation of the quantity of fuel,
which could be selected, to the maximum permissible quantity at each
instant. The force required to be exerted through the regulator
under these arrangements is, in general, greater than in the arrange-
ment shown in figure 3.

2. Limitation of Gas Temperature Ahead of Turbine

Because in the range of temperatures in question the strength of
turbine-blade material drops markedly with only a small increase in
temperature, a reliable means of preventing any overstepping of the
permissible blade temperature, which corresponds for practical pur-
poses to a certain gas temperature ahead of the turbine (reference 3),
is of great importance. In order to obtain actually at every oper-
ating state the highest output that is attainable only with the

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[7]Account of the temperature of the fuel is unnecessary for the
quantity of fuel flowing through varies only with the square root of
the density and the errors thus caused, which are in any case small,
may be partly canceled if the regulator valve is suitably constructed
as a nozzle by the simultaneous variation of the outflow coefficient
with Reynolds number.

highest permissible gas temperature, it is important that the temperature shall not fall substantially below this maximum at full power. Consequently, an exact control of the gas temperature ahead of the turbine will be found necessary.

A direct control of the gas temperature by means of a temperature-sensitive device is certainly possible but involves certain difficulties, particularly because in this case a very rapid adjusting action is absolutely necessary. Electrical apparatus may seem the obvious answer but is generally very delicate and therefore apt to cause breakdowns. For example, a sort of vapor-pressure thermometer using mercury or amalgam for a lower range and rubidium, cesium, or potassium for a higher range of temperatures might also be considered. A disadvantage of most such temperature-sensitive devices is their inertia, which may allow considerable, although brief, rises in the gas temperature above the permissible figure during acceleration.

The development of suitable equipment for the determination of temperatures of this magnitude constitutes a problem in itself and will therefore not be treated further here. Such equipment is unnecessary because an indirect determination of the gas temperature is possible with relatively simple means. The systems to be described subsequently may be used independently of the other control arrangements; in combination with other arrangements under appropriate circumstances simple methods based on other principles may also be defined for limiting the gas temperature (for example, in the jet power plant).

As shown in figure 4, the quantity of fuel supplied per kilogram of air, that is, the fuel-air mixture ratio m necessary to heat the gas from the temperature T_2 behind the compressor to the constant maximum temperature ahead of the turbine T_{3max} varies in approximately linear proportion with the temperature T_2. If the critical velocity is reached in the turbine nozzles — at lesser outputs the turbine generally is in no danger[8] — at the constant gas temperature T_{3max}, the mass flow of gas, and with it very nearly the mass flow of

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[8]An overstepping of the maximum permissible gas temperature at very low power output, that is, at low speed, can occur for only a few seconds at the most during acceleration and is certainly not dangerous in those circumstances.

air, is proportional to the pressure p_3 ahead of the turbine.[9] Consequently, for a given power plant the maximum permissible fuel quantity per unit time B_{max} may be formulated as

$$B_{max} = C_1 \, p_3 \, (C_2 - T_2)$$

where C_1 and C_2 (also C_1', C_2', C_2'' hereinafter) are constants.

This product can easily be made to govern the fuel settings, for example, by an arrangement like that in figure 5. The temperature-sensitive device a, shown in the form of a bimetallic strip, provides an adjusting motion approximately proportional to the temperature T_2; the pressure capsule b provides a setting proportional to the pressure p_3; the setting of the plug c by which the flow area of the constriction e in the fuel supply line f is regulated, as previously described in connection with figure 3, is proportional to the product of p_3 and $(C_2 - T_2)$ (reference 4, p. 19). A servomotor to provide extra power is probably unnecessary here.

Instead of ascertaining the pressure and the temperature by separate means, a gas-filled capsule (reference 5, p. 38) might be used here also. On the other hand, the measurement of the absolute pressure may be replaced very simply by the measurement of a pressure difference, for example, as follows: Behind the compressor a small quantity of air is allowed to escape into the atmosphere through a divergent nozzle provided with pressure-measuring means near its narrowest cross section where the critical velocity exists. In the range in question, the pressure difference at the measuring point, as compared to p_2, is very nearly proportional to the absolute pressure p_3 and can therefore be used for regulation.

At a given turbine speed and at constant temperature ahead of the turbine, the temperature T_2 behind the compressor is clearly a function of the temperature ahead of the compressor and therefore the temperature T_1 may even by used for regulation instead of the

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[9]The simplifying approximations, devised for the treatment of the power plant as a whole in part I of this report, are not used in the investigation of the control of fuel quantity carried out in this part; therefore, the errors in the characteristic values that were pointed out there do not occur here.

temperature T_2.[10] In reference to a compressor having the character-
istics shown in figure 2, figure 6 gives as a function of T_1 the
quantity of fuel per kilogram of air required for heating the gases
to a constant temperature T_3 (T_3 = 800° C), which falls in almost
linear proportion with increasing temperature T_1. Hence, regulation
may be based on the equation

$$B_{max} = C_1' \, p_3 \, (C_2' - T_1)$$

The same device (fig. 5) is used as for regulation by T_2, the only
required changes being in the adjustments corresponding to the various
constants. The use of the temperature T_1 for regulation has the
advantage that the temperature-sensitive device may react rather
slowly because the variations in T_1 will be slow and there will be
considerable freedom in the design and installation of the temperature-
sensitive device because air at the temperature in question is avail-
able in any desired quantity. For this reason, temperature-sensitive
devices of stronger construction may be used.

With this type of regulation, the maximum temperature occurring
ahead of the turbine is equal to the maximum permissible temperature
T_{3max} only at maximum speed; at lesser speed, the maximum temperature
is somewhat lower, corresponding to the smaller temperature rise in
the compressor.[11] In the equilibrium condition, this temperature
rise in the compressor is without effect when the highest temperature
is attained only at the highest speed, whereas at lower speed, a lower
gas temperature T_3 is automatically established. In this case,
only during acceleration does this decrease of temperature involve a
certain sacrifice of power, that is, a decreased acceleration. In
the jet power plant, for example, the temperature T_3 falls very
rapidly with decreasing power output, as will be shown in part III.
Even here the decrease in acceleration is not serious. The behavior
of turbine-propeller jet and ducted-fan jet power plants has not yet
been investigated in this respect.

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[10]Use of the pressure p_1 for regulation instead of p_3 is
also fundamentally possible; however, in such a system the influence
of temperature variations becomes very marked — corresponding in
effect to the curve of $m(p_2/p_1)$ in figure 6 — therefore regulation
in accordance with the pressure p_3 is generally to be preferred.

[11]Under certain circumstances, this rise in the compressor may
even be desirable because with decreasing speed the blade temperature
increases, although the effect of this increase tends to be counter-
acted by the reduction of centrifugal stresses.

If it is also desired to maintain accurately the maximum temperature T_{3max} at lower speed, this maintenance can be done easily by taking into account the speed, namely by basing the regulation on

$$B_{max} = C_1' \; p_3 \; [C_2'' - T_1 + f(n)]$$

Thus only the effect of speed must be superimposed on that of temperature, for example, by shifting the temperature-sensitive device in figure 5 in accordance with a function of the speed or by using the regulating system shown in figure 8, which will be described subsequently.

Because the effect of the temperatures T_1 or T_2 on the quantity of fuel to be controlled is not very great, they may be disregarded entirely and the regulation of the maximum permissible quantity of fuel based solely on a function of p_3. Figure 7 shows the errors thus introduced in a compressor having the characteristics plotted in figure 2. For a temperature difference of $30°$ C from Ina [NACA comment: International standard atmosphere], the errors are in this case of the order of magnitude of 5 percent; the flight speed has little effect. In order to be certain of avoiding any overstepping of the permissible gas temperature ahead of the turbine, the setting for any given pressure p_3 must correspond to a quantity of fuel small enough to allow for the maximum possible atmospheric temperature. Consequently, when atmospheric temperature is actually lower than maximum, a smaller quantity of fuel is supplied and hence a lower power output obtained than would be the case if air temperature was made a factor in the regulating system.

When the requirements of accuracy of regulation are high, this system is inappropriate; the simplification obtained is not great because the necessity of an exact reponse to pressure remains, whereas the response to temperature need not be so exact.

3. Limitation of Speed

A limitation of the speed by limiting the quantity of fuel supplied may be attained in the following simple manner: when the permissible speed is exceeded, a tachometric control opens an overflow valve in the fuel line to the injection nozzles; this arrangement can be made with familiar constructional elements.

Even when the speed is already subject to other controls, this limitation of the quantity of fuel may be necessary to avoid a brief

overstepping of the permissible speed during the response period of the other regulating arrangements if those arrangements are subject to noticeable inertia; also an auxiliary means of limiting the speed seems advisable as a safety measure.

4. Avoidance of Unstable Region of

Compressor Operating Range

If the volume of air drawn into the compressor falls below a certain value that is dependent upon the speed and temperature $(n/\sqrt{T_1})$ at any given moment, in individual stages of the compressor a breakdown of the flow over the blades accompanied by a marked drop in pressure head and efficiency arises. Stable operation is then no longer possible. The dash-dot line in figure 2 shows the limit of the region of stable operation in the characteristics diagram. Beyond the unstable region, there is at smaller values of $V_1/\sqrt{T_1}$ another stable region, which is not shown in the diagram as it is of no importance because of the poor efficiencies and low pressure heads.

Even if operation of the compressor in the unstable region would not lead to any damage, avoidance of this region is still important because of engine output. This precaution also applies to the brief period of acceleration because in the unstable region a reduction rather than an increase in speed might occur because of the drop in pressure head and efficiency of the compressor.

These difficulties will arise only if the boundary curve lies at the edge of the region in which the compressor actually operates. This position of the curve is not the case, for example, in the characteristics diagram shown in figure 2, which is based on blade forms deliberately chosen as being especially favorable in this respect. The diagram is, however, questionable and must therefore be tested by experiment to determine whether a generalization is permissible here.

With customary compressor design, an unstable condition generally initially arises in the first or last stage (boundary curve above or below the break, respectively, in fig. 2); this unstable condition usually occurs when in the stage in question the flow coefficient Φ, that is, the ratio of mean axial velocity at the inlet into the rotor to peripheral velocity, falls below a certain value (more or less dependant upon Mach number and possibly also on Reynolds number).

When critical velocity is attained in the turbine nozzles, the flow coefficient Φ of the last stage is nearly proportional to

$T_2/n \ \epsilon_n\sqrt{T_3}$ in which ϵ_n is the compression ratio in the last stage.
With a given change of temperature ahead of the compressor, the temperature behind the compressor changes relatively less the higher the pressure head. A change in speed in a compressor having a large pressure head (H_{ad} about 20,000 m) will be largely balanced by the simultaneous change in T_2; consequently, avoidance of operation of the last stage in the unstable region in compressors of higher pressure heads will generally be easier than in those with lower adiabatic heads.

The relations are less favorable in the first stage, the flow coefficient of which, at critical velocity in the turbine nozzles, is approximately proportional to $(p_2/p_1) \ T_1/n\sqrt{T_3}$. A change in T_1 corresponds to a change in p_2/p_1 in the opposite direction; a change in n results in a change in p_2/p_1 in the same direction. As a rough estimate shows, T_1 and p_2/p_1 cancel each other in respect to their influence on the flow coefficient at medium pressure heads; n and p_2/p_1 already counterbalance at very low pressure heads. At great pressure heads, the influence of p_2/p_1 predominates, especially over that of n and more so in proportion as the pressure head of the compressor increases.

Thus in the region of lower speed, the boundary curve will shift closer to the normal operating region of the compressor in proportion as the pressure head is larger Furthermore, a drop in the inlet temperature T_1 produces a decrease in small pressure heads and an increase in the distance between the normal operating region and the lower part of the boundary curve (the part determined by the first stage) in large pressure heads.

Consequently, special measures become necessary in many cases, particularly with compressors having high pressure heads, to limit the operating range of the power plant to the stable region of compressor operation in equilibrium condition and especially during acceleration. This limit may be accomplished most simply by limitation of the gas temperature ahead of the turbine, that is, by limitation of the quantity of fuel supplied.

In order to reach high power output as rapidly as possible when accelerating, it is again desirable to make full use of the permissible operating range, that is, to regulate as exactly as possible in accordance with the boundary curve of the compressor-characteristics diagram. Such a form of regulation may be derived from the following considerations:

From figure 2 it is at once apparent that the permissible temperature ratio T_3/T_1, as determined by the boundary curve, is a function of $n/\sqrt{T_1}$. Because the fuel-air mixture ratio m is dependent only on T_3 and T_2 and because T_2/T_1 is also a function of $n/\sqrt{T_1}$, for a particular power plant the following applies at the boundary curve:

$$m = f\left(T_1, \frac{n}{\sqrt{T_1}}\right) = f_1\left(T_1, n\right)$$

If critical velocity is attained in the turbine nozzles, then as previously described, the corresponding boundary value of the quantity of fuel per unit time B_{max} is proportional to $m(p_3)$.

Regulation on this basis may be accomplished in a simple manner (fig. 8) with the aid of a cam surface a, which is revolved approximately in proportion to the speed and shifted axially in proportion to T_1 by the temperature-sensitive device b; the cam action of the surface displaces the lever c. Thus each speed and each temperature produces a certain setting of the lever c that is proportional to the value of m. The multiplication of the value of m with the pressure p_3 occurs in the same manner as previously indicated for the limitation of the gas temperature ahead of the turbine.

Because it is also true in the case of limitation of the gas temperature T_3 that the permissible fuel quantity B_{max} is proportional to $m(p_3)$ and the mixture ratio m is a function of T_1 and n, the limitation of the gas temperature may be carried out with the same regulating device by using an appropriate development of the cam surface a. Thus the system of regulation according to figure 8 at the same time replaces that of figure 5.

In the region of very low speed in which critical velocity is not attained in the turbine nozzles and in which, consequently, the method of regulation described no longer serves its purpose, operation of the first stage of the compressor in the unstable region is in general scarcely serious. In particular, the last stages of the compressor, operating in the region of negative pressure heads, constitute in such a case a strong influence toward stabilization because a decrease in pressure head and efficiency in the first stages is in part canceled by a corresponding increase in the last stages.

III. THEORETICALLY EXACT CONTROL OF ADJUSTABLE PARTS

1. Conclusions From Principles of Similarity

In order to enable the closest possible accommodation of the power plant to the operating conditions at each given moment, certain parts of the power plant are usually designed adjustable, for example, the jet nozzle of the jet engine. In this section, the control of these "adjustable parts" will first be treated theoretically on the basis of general considerations and, in particular, of the principles of similarity presented in part I and also under the assumption that the requirements of best possible utilization of fuel at part load and maximum possible power output, when set for full load, are to be exactly fulfilled under all possible operating conditions. In the practical design, compromises will be made and the regulating system will be very much simplified but it is first desirable to obtain a clear insight into the fundamental relations by study of the ideal case.

From this point on, "adjustable parts" will be understood as those controllable parts of the power plant by which the flow within or into the power plant is directly influenced; the fuel-supply devices are not so classified as the fuel supply takes effect indirectly through the temperature rise in the combustion chamber. Adjustable parts are, indeed, not fundamentally necessary but it is clear that because of the better accommodation to various operating conditions either a higher power output, better fuel utilization, or both can generally be obtained. The question whether a particular part of an engine should be designed adjustable is to be decided by a test check, mathematical if necessary, to determine if the gain will be worth the cost.

As was shown in part I, at given settings of all adjustable parts of a given power plant the determination of two independent characteristic values, in effect, determines all other characteristic values. The dimensionless quantities such as ratios of pressure, temperature, and velocity, and Mach numbers, efficiencies, and characteristic values derived from these, such as $n/\sqrt{T_1}$, as well as the characteristic values for thrust and for specific and absolute fuel consumption are included as characteristic values.

The first case considered will be that in which the power plant has one adjustable part, for example, the jet-nozzle flow area in the jet engine. Whereas two characteristic values, for example, the Mach number of flight speed Ma_0 and $n/\sqrt{T_1}$ may be chosen at will, a third, the temperature ratio T_3/T_1, must be so determined by the

setting of the adjustable part from moment to moment that for every
value of power output the least possible fuel consumption is attained.
So long as speed and gas temperature remain below the permissible
maximum, the adjustable part is to be regulated as a function of two
independent characteristic values, for example, p_1/p_0 and $n/\sqrt{T_1}$.
Should one of these boundary values be reached, the regulator must
generally keep this value constant with rising power output until the
second boundary value is also reached.

If the design includes the arrangements described in the pre-
ceding section for the direct limitation of the quantity of fuel per
unit time, these arrangements will prevent an overstepping of the
speed and the quantity of fuel permissible at each instant. However,
care must be taken that at full-power setting the maximum speed and
maximum gas temperature T_{3max} are actually attained. Because of the
variability of T_1, the characteristics T_3/T_1 and $n/\sqrt{T_1}$ assume
various values for n_{max} = constant and also for T_{3max} = constant
and therefore the operating conditions at the boundary curve are no
longer similar.

Various relations result according to whether the speed or the
fuel supply is, within the permissible limits, arbitrarily set. The
case of speed control will be examined first.

2. Direct Control of Adjustable Part

In Selection of Fuel Flow

If, as is practically always the case with the TL power plant,
under all operating conditions the speed limit is the first condition
to be reached as power output rises, the gas-temperature limit being
reached only later; then after the speed limit is attained, a regu-
lation of the adjustable part that will keep the speed constant will
suffice. Because in the transition to higher power, a temporary
excess of turbine power due to the temporary rise in gas temperature
as a result of increased fuel flow is available, the higher power
output automatically establishes itself.

However, if in one part of the operating range the maximum tem-
perature is first reached as the power output rises and only there-
after the maximum speed is reached, additional means must be provided
to insure that as the maximum permissible gas temperature is approached
the adjustable part is so moved that the speed increases. Without

such additional means, after the maximum gas temperature was reached
a further increase in the quantity of fuel that would produce an
increase of speed would be impossible.

A diagram of a system for theoretically exact regulation according
to these principles is presented in figure 9. The quantity of fuel is
here determined by the power lever a in the fuel-injection system b;
this system simultaneously prevents an overstepping of the maximum
quantity of fuel in the manner previously described (figs. 3, 5,
and 8). The source of control for the adjustable part R is the
cam surface c, which revolves about the axis d in proportion to
$n/\sqrt{T_1}$, shifts axially in proportion to p_1/p_o, and displaces the
lever e. The rod f moves the adjustable part, possibly with the
aid of a servomotor. The fulcrum of the lever e at the end of the
rod h remains fixed so long as the speed does not exceed the maximum
speed n_{max}. When this maximum speed is exceeded, the very sensitive
tachometric control device g displaces the rod h, carrying the
fulcrum of lever e from the fixed rest i and thereby so shifting
the adjustable part that the speed remains approximately constant.

Should the maximum permissible gas temperature be reached before
the maximum speed, then, as indicated by the rod k shown as a dashed
line, immediately before the mechanism that limits the quantity of
fuel by opening the overflow valve f in figure 3 begins operating,
the rest i is displaced upwardly whereby the adjustable part is so
shifted that the speed is increased.

3. Direct Control of Adjustable Part In Selection of Speed

If the power lever is so arranged that its movement selects the
speed rather than the quantity of fuel, the control of the adjustable
part during operation below the maximum speed and the maximum per-
missible gas temperature will naturally remain basically the same as
in the pilot's manual selection of fuel flow. The quantity of fuel
will now be so regulated as a function of the speed that the selected
speed will take effect. Conversely, there will be substantial changes
in the system of regulation after the maximum speed or maximum per-
missible quantity of fuel is reached. Here the value for T_3/T_1,
$n/\sqrt{T_1}$, or both corresponding to the minimum specific fuel consump-
tion at each moment cannot be put into effect, instead the value
T_3/T_1, $n/\sqrt{T_1}$, or both corresponding to the desired power output
is varied independently of the other quantities; consequently, in
this case the setting of the adjustable part is dependent upon three
characteristic values p_1/p_o, $n/\sqrt{T_1}$, and T_3/T_1.

If the maximum speed is reached before the maximum permissible gas temperature, with further increase of output the adjustable part is to be shifted in the direction of increasing output, starting from its position (dependent on p_1/p_0 and T_1) when maximum speed was reached. The limit setting for maximum output (n_{max}, T_{3max}) that must be put into effect by the regulating system is also dependent upon p_1/p_0 and T_1.

An exact description of the layout of such a system of regulation will not be made because for theoretically exact fulfillment of the requirements an exact description would be quite complicated; in practice, however, considerable simplification is possible with practically no adverse effect on the over-all result. Such a simplified regulating system for the jet engine is presented in figure 8, part III.

If the maximum permissible gas temperature is reached before the maximum speed, no special measures are necessary for control of the adjustable part under the assumption, which is probably always correct, that, at the maximum permissible gas temperature with a given setting of the adjustable part and a decreasing speed, excess turbine power, which is not especially important, exists. In the region in which the necessary arrangements for the direct limitation of the quantity of fuel come into operation, the actual speed is less than that selected through the speed regulator.

4. Indirect Control of Adjustable Part

Instead of directly controlling the adjustable part by the regulating system, control is also possible in terms of the speed or of a characteristic value that varies markedly with the speed in such a manner that the speed assumes at each moment the required value. If, for example, the power lever is arranged for direct selection of the quantity of fuel, the value of $n/\sqrt{T_1}$ may be so determined as a function of a characteristic value of the quantity of fuel per unit time, $B/p_3\sqrt{T_1}$ or $B/p_3 T$ (see part 1) and of the pressure ratio p_1/p_0 that the specific fuel consumption attains its optimum value. Movement of the adjustable part under the control of n or $n/\sqrt{T_1}$ will then establish the value of n or $n/\sqrt{T_1}$ determined at each given moment. If the pilot's manual control lever is arranged to select speed, the regulating system may in the same manner determine the characteristic value of the quantity of fuel as a function of $n/\sqrt{T_1}$ and p_1/p_0, and the setting of the adjustable part may again be governed by the speed.

With regard to regulation after the maximum speed or the maximum permissible quantity of fuel has been reached, the same considerations apply as previously set forth in the direct control of the adjustable part.

The system for the direct limitation of quantity of fuel may in this arrangement be combined with the system for determination of the characteristic value of the quantity of fuel per unit time.

5. Control of Several Adjustable Parts

Later investigations will show whether it will prove necessary or desirable to make several parts of turbine-propeller jet and ducted-fan jet power plants adjustable, for example, the jet-nozzle flow area as well as the propeller pitch.

Theoretically, if there are two adjustable parts both should be governed by two suitable characteristic values, for example, p_1/p_0 and $n/\sqrt{T_1}$, that is, by different functions of these two quantities. In figure 9, for example, two different but commonly actuated cam surfaces must be provided for the two adjustable parts, however, strictly speaking, the speed limitation would be different for the two adjustable parts and would be a function of p_1/p_0. The displacement of the fulcrum of the lever e in figure 9 should thus be accomplished by an additional cam surface for each of the adjustable parts, these surfaces expressing functions of p_1/p_0 and of the speed n (not quite the same as n_{max}). In practice, however, much simpler arrangements can presumably be used, therefore any more detailed discussion of theoretically exact regulation may be omitted.

SUMMARY

It is shown how an overstepping of the permissible gas temperature ahead of the turbine, of the permissible speed, or when necessary even the operation of the compressor in the unstable region may be prevented in a simple manner by limitation of the quantity of fuel. For the determination of the quantity of fuel supplied per unit time, it is appropriate to use the pressure drop at a point of constriction with controllable flow area, which is built into the fuel line. On the basis of the investigations, possible means are suggested and visualized as schematic designs for the direct limitation of the quantity of fuel. These proposals are based on the

following considerations: The quantity of fuel per unit time with
which the maximum temperature ahead of the turbine is attained is
proportional to the product of the pressure ahead of the turbine and
a practically linear function of the temperature behind the compressor
or is a product of the temperature ahead of the compressor and, for
example, the speed; therefore the limitation of the quantity of fuel
when maximum temperature ahead of the turbine is reached can be
accomplished in terms of these quantities. The quantity of fuel at
which the unstable operating region of the compressor is reached is
also proportional to the product of the pressure ahead of the turbine
and a function of the temperature and the speed. If consideration
of the unstable operating region of the compressor is necessary, the
same setup may be used for both problems. Such a regulating system
may be applied to jet, turbine-propeller jet, and ducted-fan jet power
plants. If only limitation of the gas temperature in equilibrium con-
dition is required, simple means in conjunction with the other regu-
lating devices, if desired, may be devised for this purpose; these
means will be discussed in subsequent reports.

On the basis of the principles of similarity, some general
principles are derived for a system of exact regulation of the adjust-
able parts of a power plant (for example, jet nozzle and adjustable-
pitch propeller), which at part load will give the theoretically opti-
mum value of specific fuel consumption and when set for full power
will give the highest possible output. According to these principles,
for the attainment of the theoretical optimum value of specific fuel
consumption the adjustable parts are to be regulated in accordance
with functions of two characteristic values, for example, the pressure
ratio in the impact scoop and the quotient of speed divided by the
square root of the temperature ahead of the compressor, until as power
output increases the maximum permissible gas temperature ahead of the
turbine or the maximum speed is reached. An indirect control of an
adjustable part governed by the speed or by a characteristic value
that varies markedly with the speed is also possible. Upon further
increase of power output, the gas temperature or the speed, depending
on which shall have reached its limit, requires controlling. The
considerations bearing upon this function in each different arrange-
ment are considered in detail.

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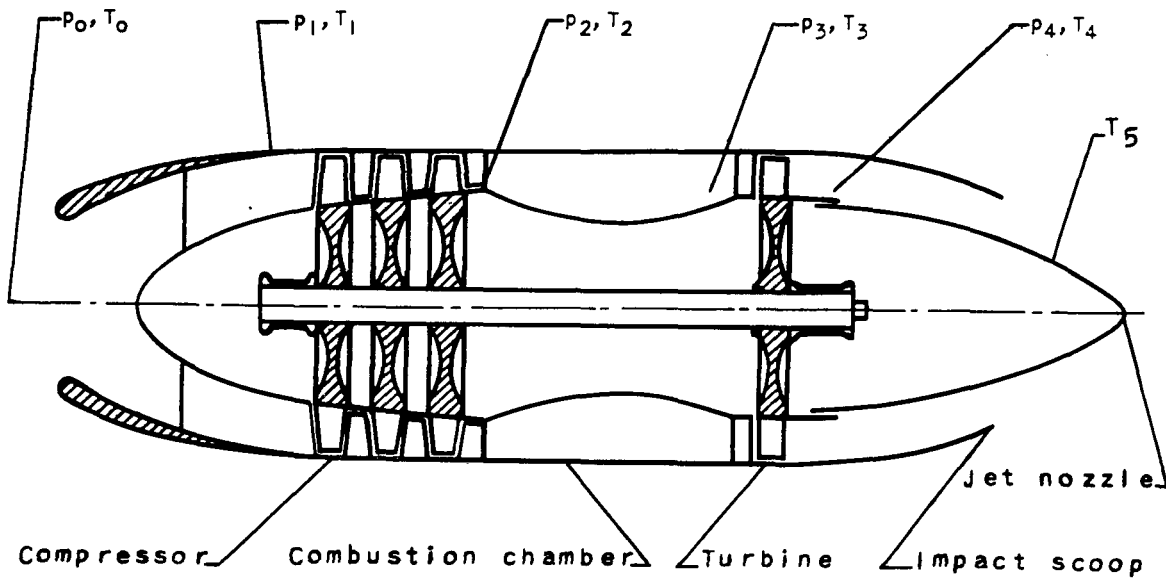
Figure 1. — Diagram of turbojet power plant.
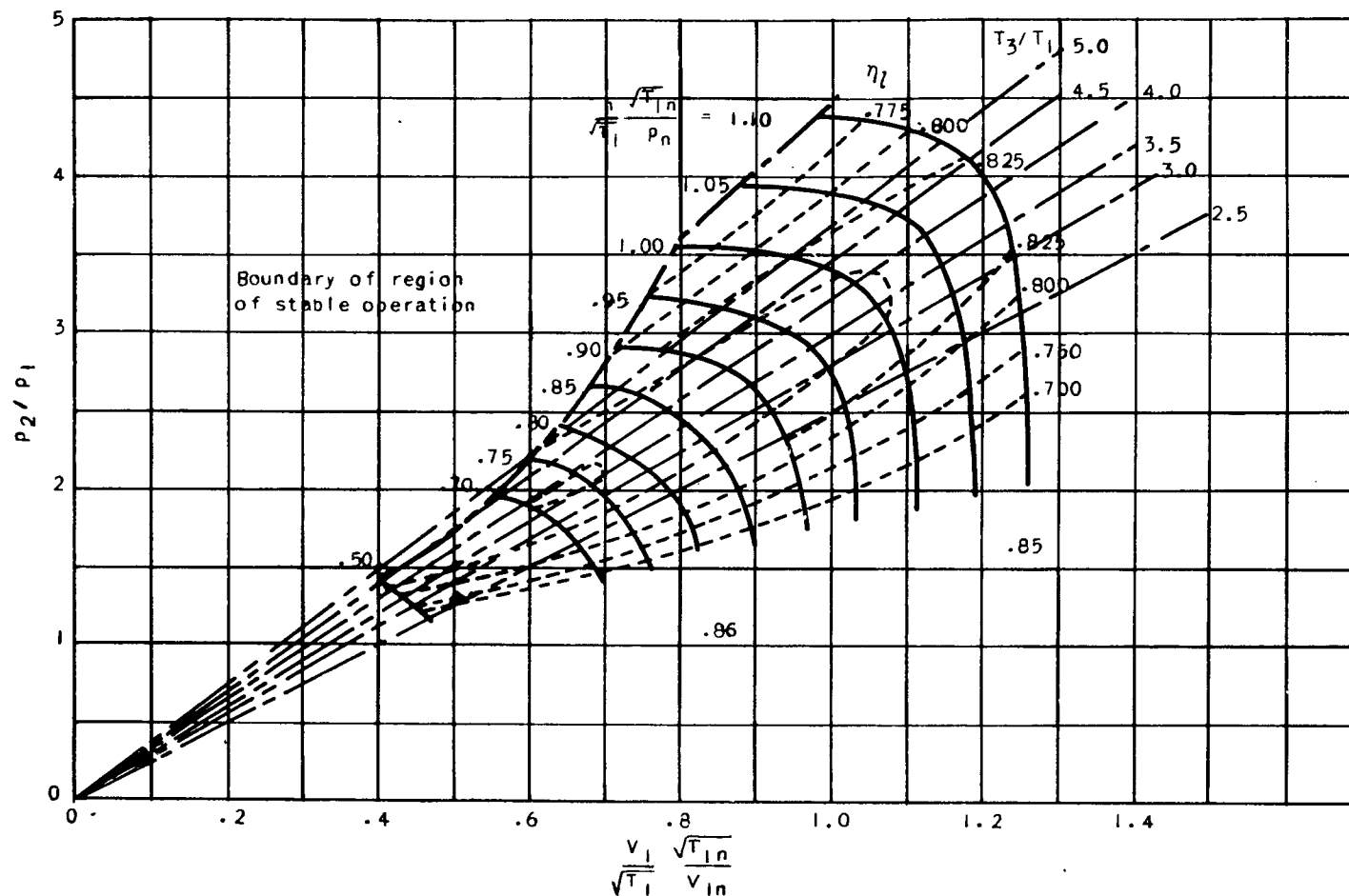
Fig. 2

Figure 2. — Example of characteristics diagram of eight–stage compressor approximately
computed from measurements by AVA at Göttingen on individual stages.
Subscript n denotes design condition.

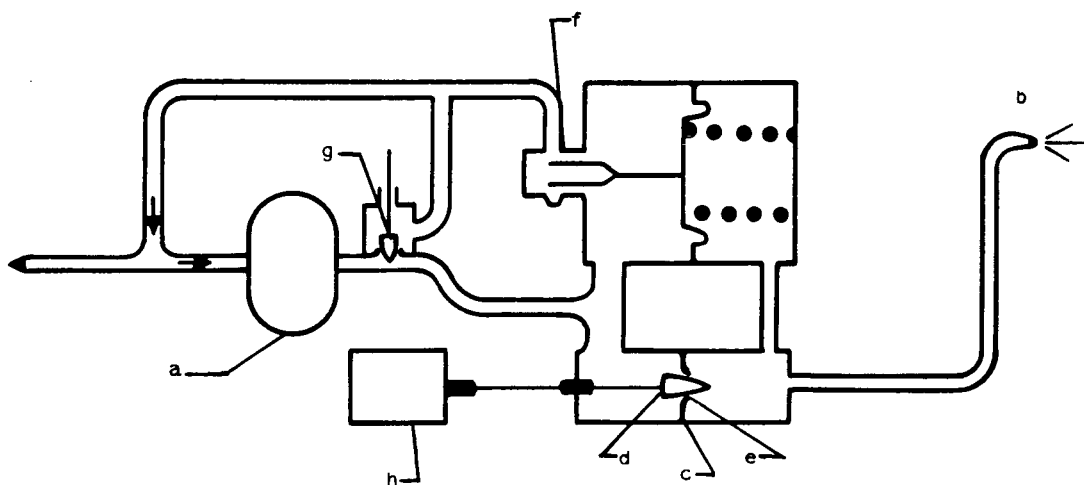Lines T_3/T_1 are valid for constant turbine–nozzle area at critical velocity.

Figure 3. — Diagram of arrangement for determination and
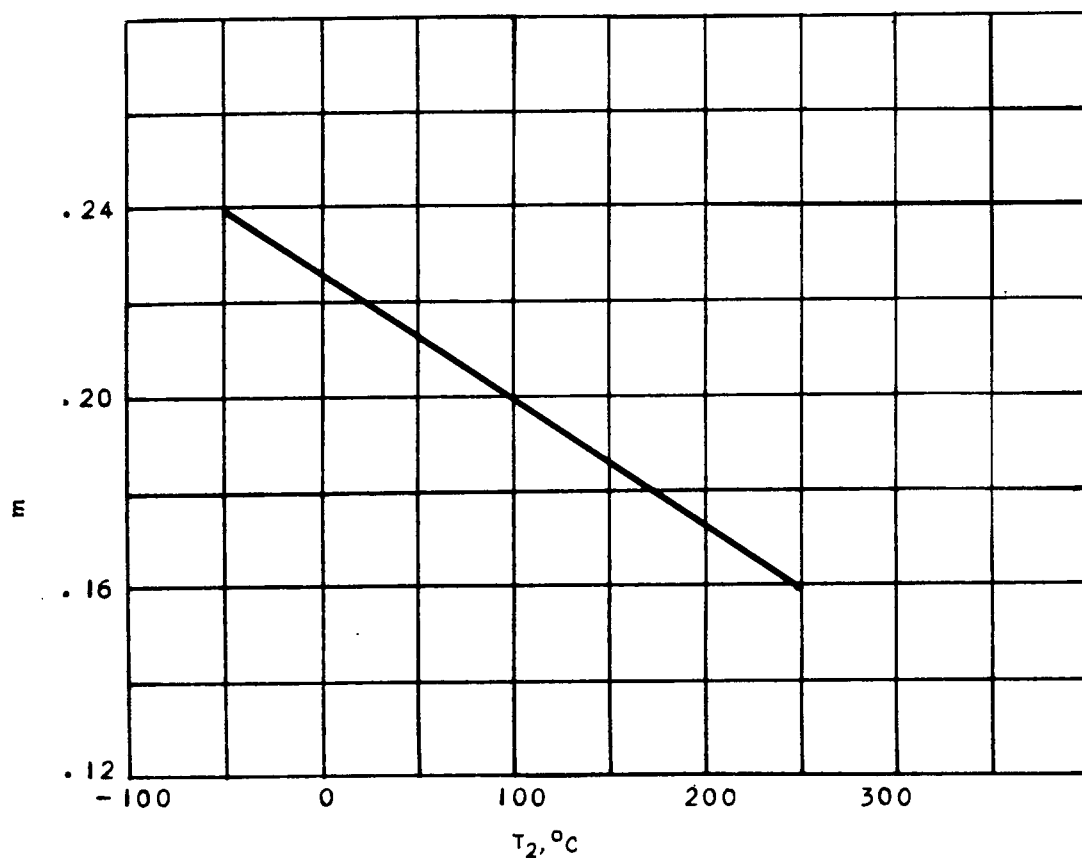limitation of quantity of fuel per unit time.

Fig. 4   NACA TM No. 1143

Figure 4. — Fuel—air mixture ratio m at constant gas tem-
perature ahead of turbine $T_{3max} = 800°C$ as function of
temperature T_2 behind compressor. Efficiency of combus-
tion chamber η_b = 95 percent.
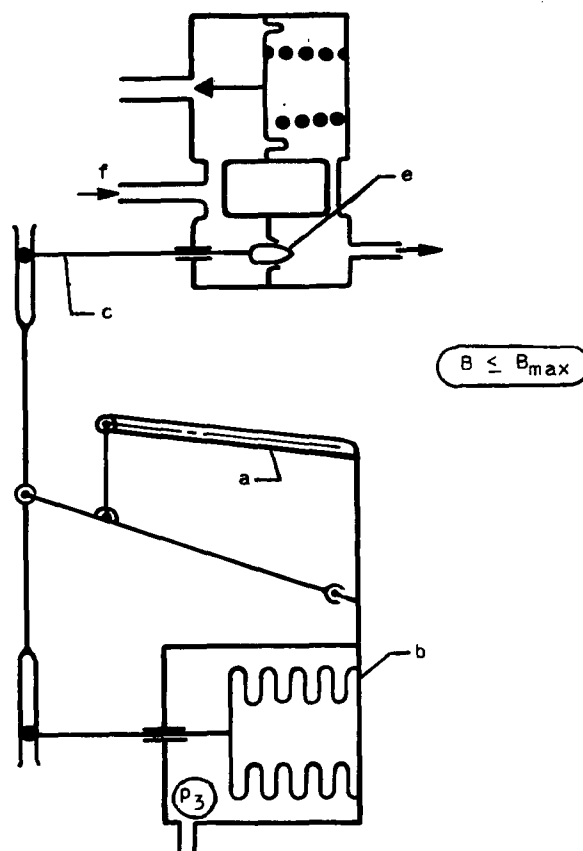
Figure 5. – Diagram of arrangement for limitation of fuel
   quantity supplied at maximum permissible gas temperature.

Fig. 6   NACA TM No. 1143
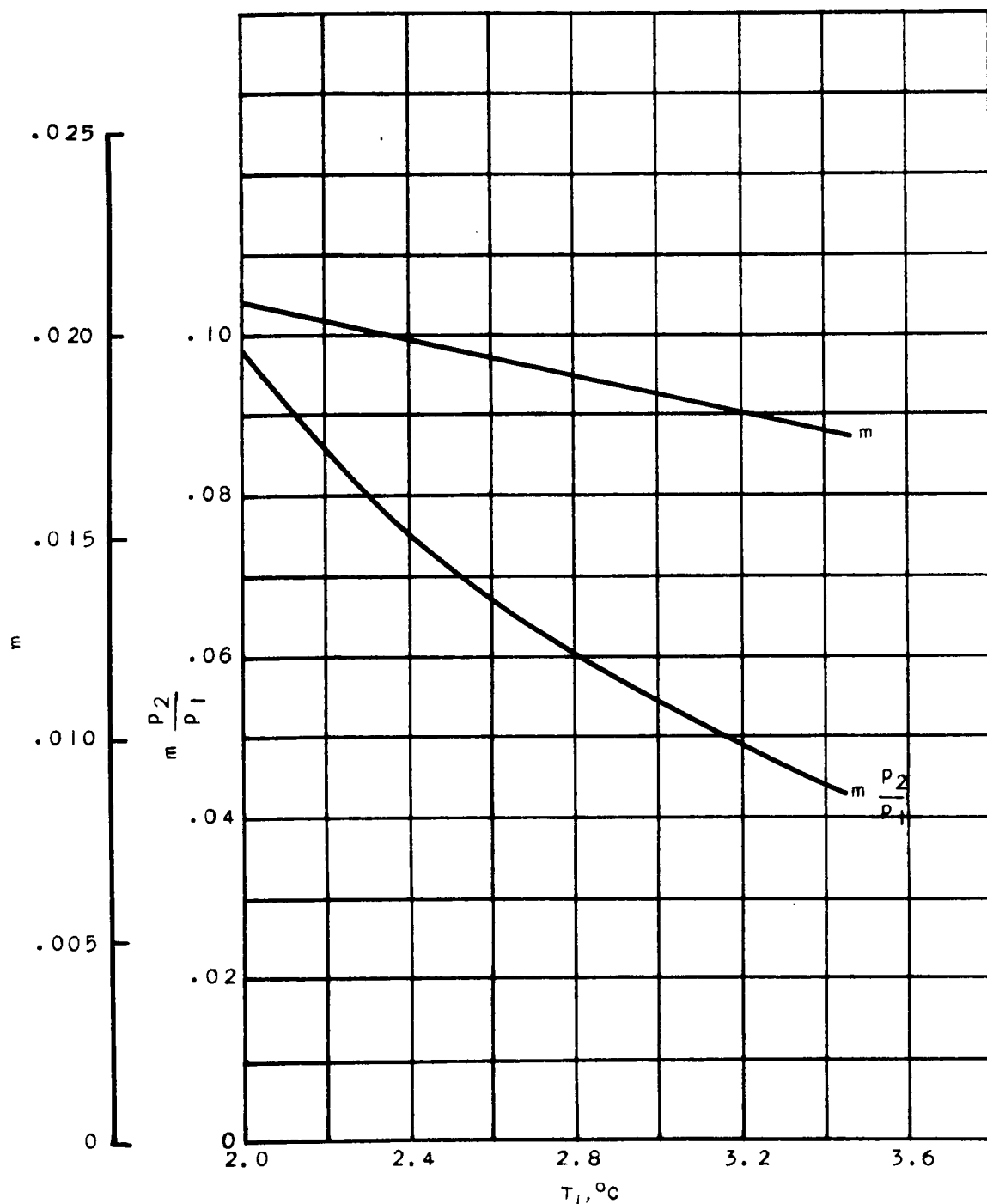
Figure 6. – Fuel–air mixture ratio m and product of m and
pressure ratio p_2/p_1 in compressor at constant gas tempera-
ture ahead of turbine T_3 = 800° C as functions of tempera-
ture T_1 ahead of compressor for a compressor the charac-
teristics of whicn are plotted in figure 2. Efficiency of
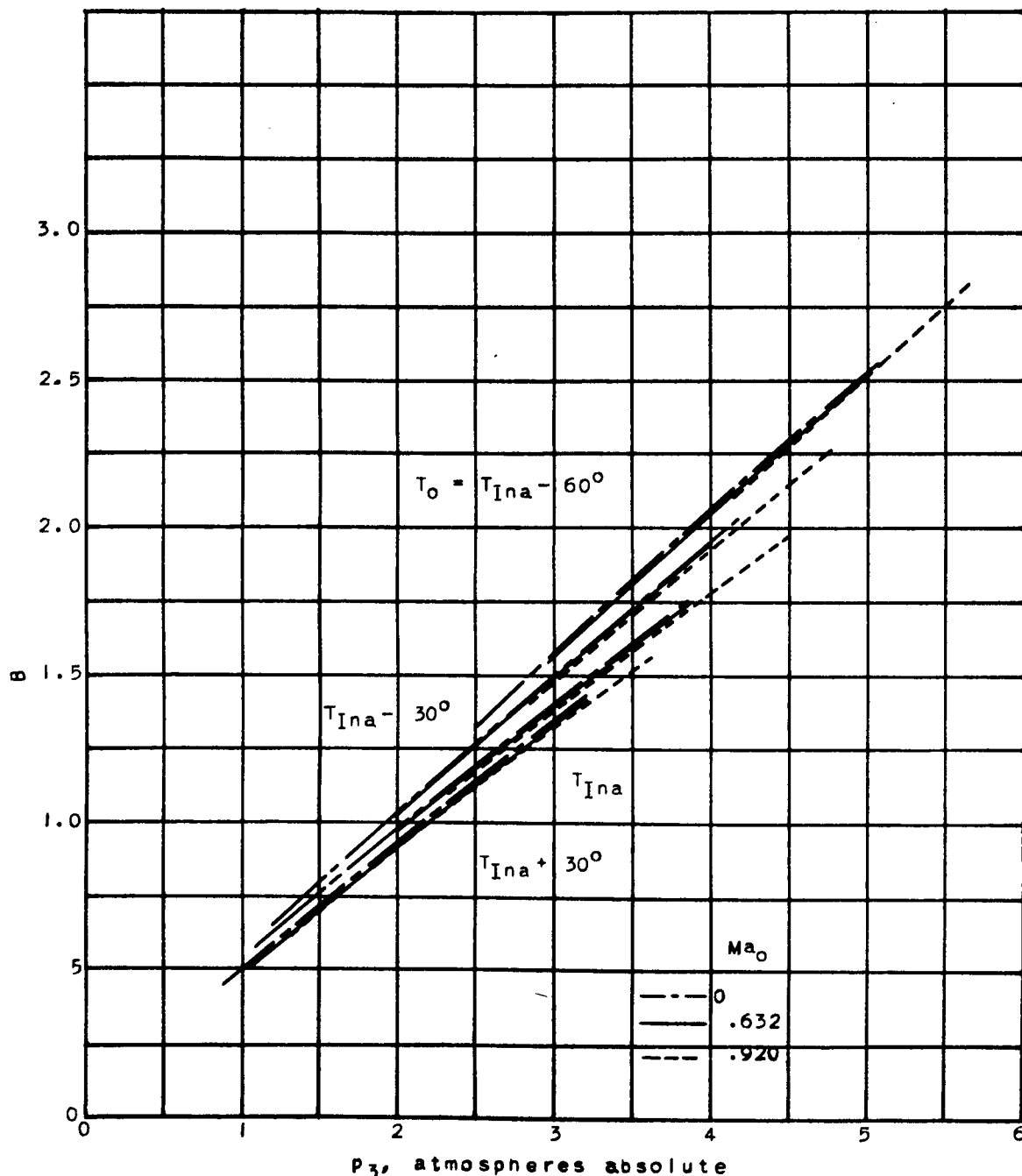combustion chamber η_b = 95 percent.

Figure 7. – Quantity of fuel per unit time B required to pro-
duce constant gas temperature ahead of turbine $T_3 = 800°$ C
as a function of pressure ahead of turbine p_3 plotted for
various atmospheric temperatures T_0 and various Mach
numbers of flight speed Ma_0 and computed for compressor
with characteristics shown in figure 2. (T_{Ina} = tempera-
ture according to Ina standards; B is equal to unity for
6 km Ina and Ma_0 = 0.632 and corresponds to w_0 = 200 m/sec)

Fig. 8   NACA TM No. 1143
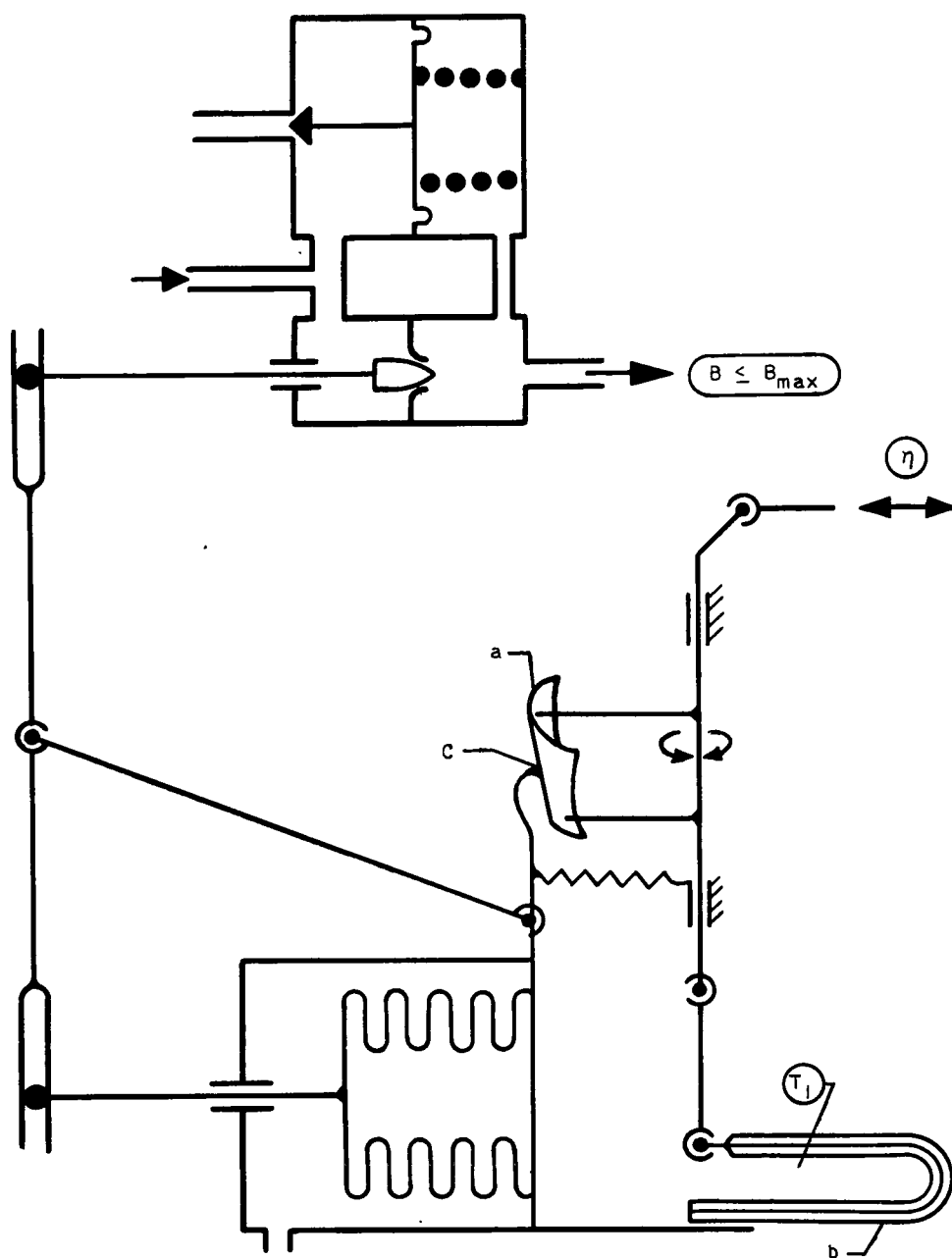
$B \leq B_{max}$

Figure 8. — Diagram of arrangement for limitation of quantity
of fuel supplied at boundary of unstable operating region
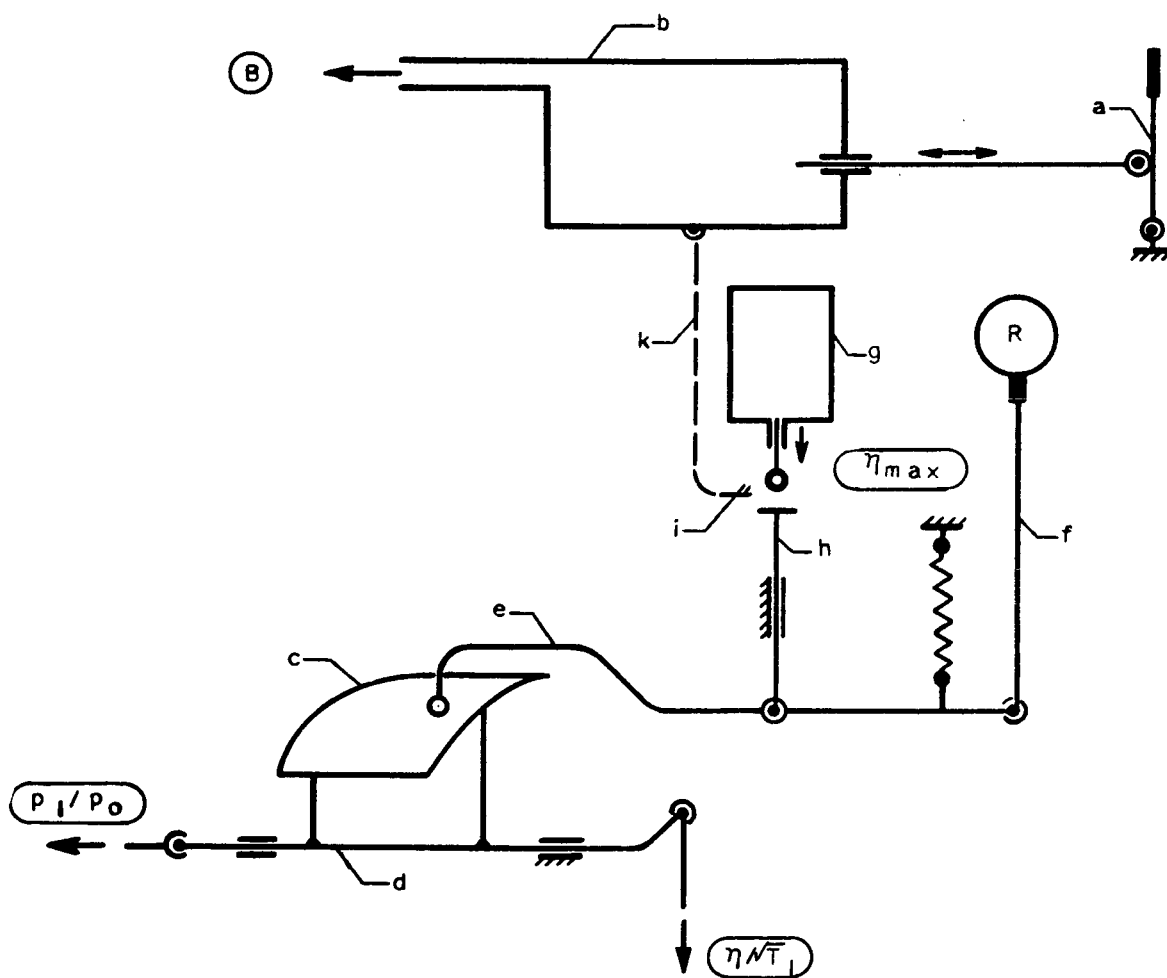of compressor and at maximum permissible gas temperature.

Figure 9. – Diagram of system of theoretically exact control
of adjustable part R when pilot's manual control lever
directly governs quantity of fuel.